Future Physics with CMS detector at HL-LHC

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On behalf of CMS experiment

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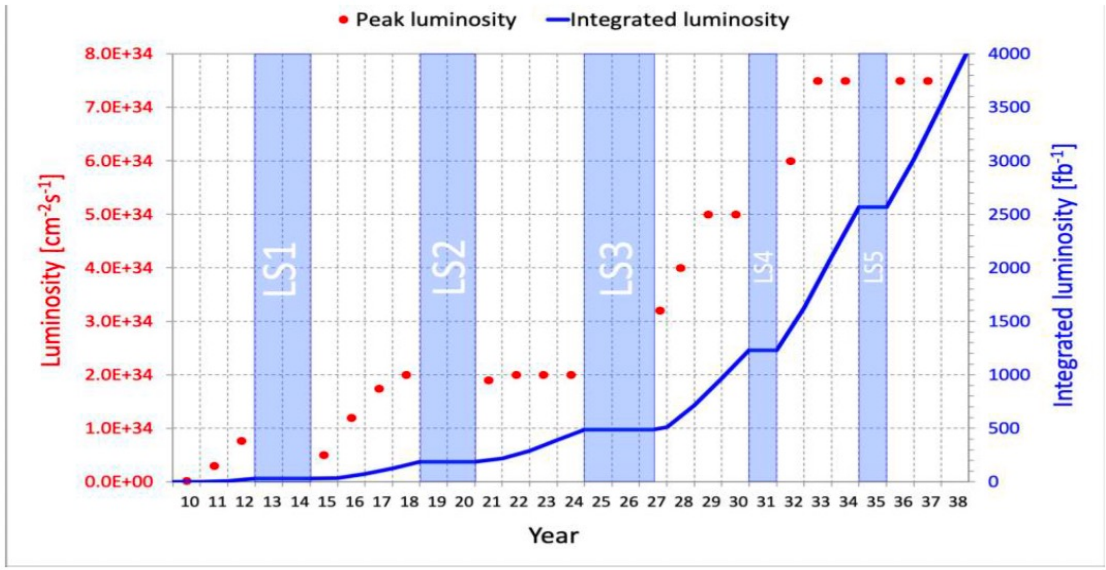
WG6: Future Experiments,

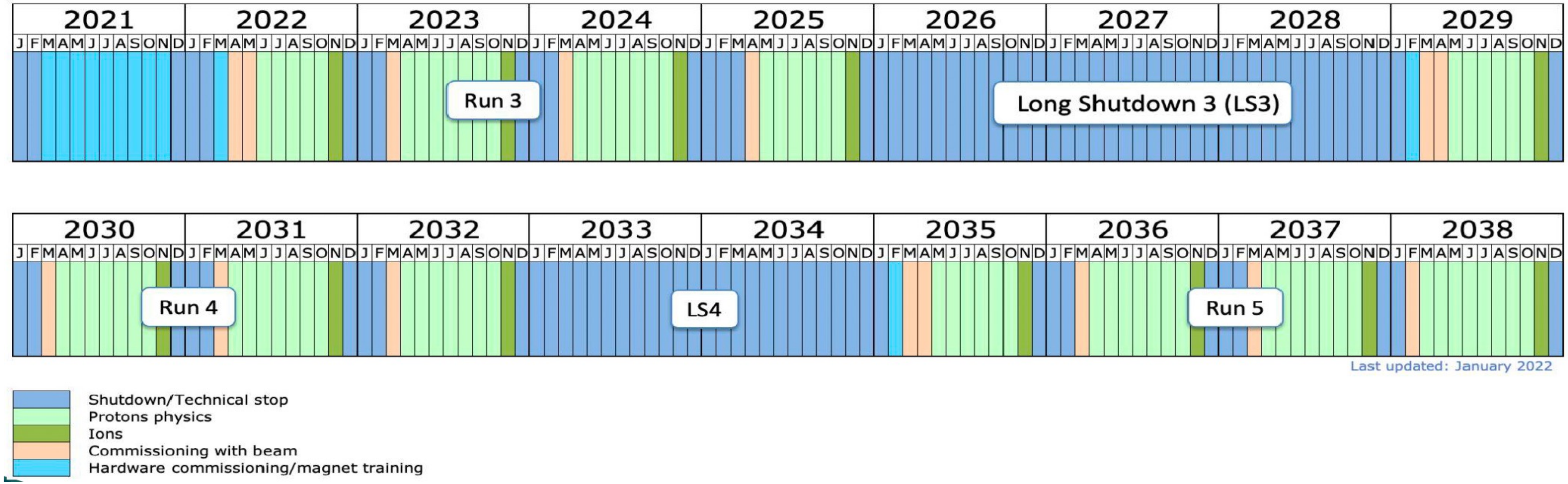
XXXI International Workshop on Deep Inelastic Scattering and Related Subjects (DIS2024),

Grenoble, France

The High Luminosity LHC (HL-LHC) Upgrade

HL-LHC goal is to achieve ≈20x more data than recorded so far





Snowmass White Paper Contribution: ATLAS & CMS

Physics with the Phase-2 ATLAS and CMS Detectors. ATL-PHYS-PUB-2022-018

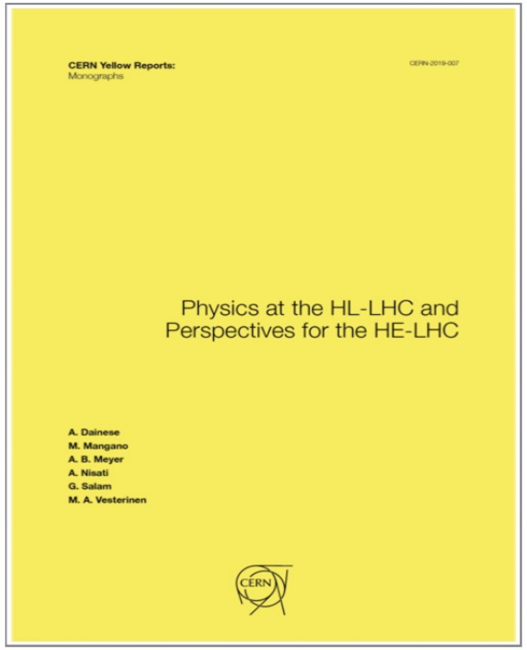
Contents

Summary of earlier results
- mainly from the 2018-19 Yellow Reports (YRs)
- 1-page summaries of new results

Projections to HL-LHC

- **HL-LHC projection results mainly based on:**
  - 2018 Yellow Report
  - substantial update in the Snowmass2021 report
- **Strategies for the projection:**
  - extrapolations of (partial/full) Run-2 results to HL-LHC luminosity
  - parametric simulations based on upgraded detectors

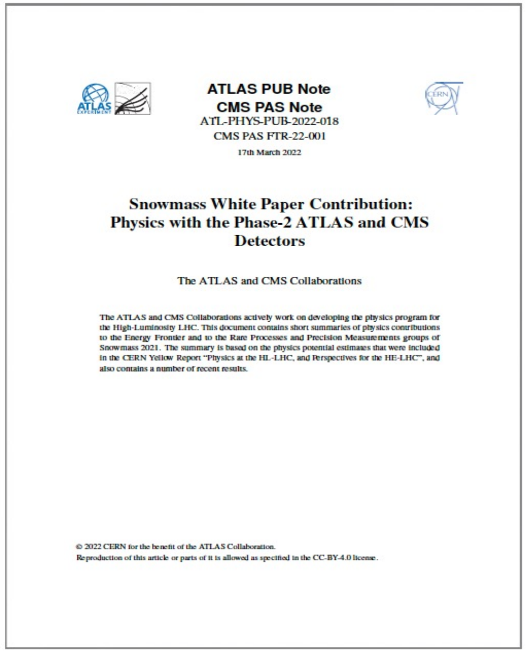
- **Uncertainty schemes:**
- YR18 systematics uncertainties (baseline):
  - theoretical uncertainties: reduced by half
  - most experimental uncertainties: scaled down with 1/sqrt(L)
  - luminosity uncertainty: aiming at 1%
  - uncertainties due to the limited number of simulated events are typically neglected
- alternatively, to understand the impacts of systematics
  - Run-2 systematic uncertainties
  - statistical-only uncertainties


CERN Yellow Reports:
Monographs
CERN-2019-007

Physics at the HL-LHC and
Perspectives for the HE-LHC

A. Dainese
M. Mangano
A. B. Meyer
A. Nisati
G. Salam
M. A. Vesterinen

CERN


ATLAS PUB Note
CMS PAS Note
ATL-PHYS-PUB-2022-018
CMS PAS FTR-22-001
17th March 2022

Snowmass White Paper Contribution:
Physics with the Phase-2 ATLAS and CMS Detectors

The ATLAS and CMS Collaborations

The ATLAS and CMS Collaborations actively work on developing the physics program for the High-Luminosity LHC. This document contains short summaries of physics contributions to the Energy Frontier and to the Rare Processes and Precision Measurements groups of Snowmass 2021. The summary is based on the physics potential estimates that were included in the CERN Yellow Report "Physics at the HL-LHC, and Perspectives for the HE-LHC", and also contains a number of recent results.

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4 tops

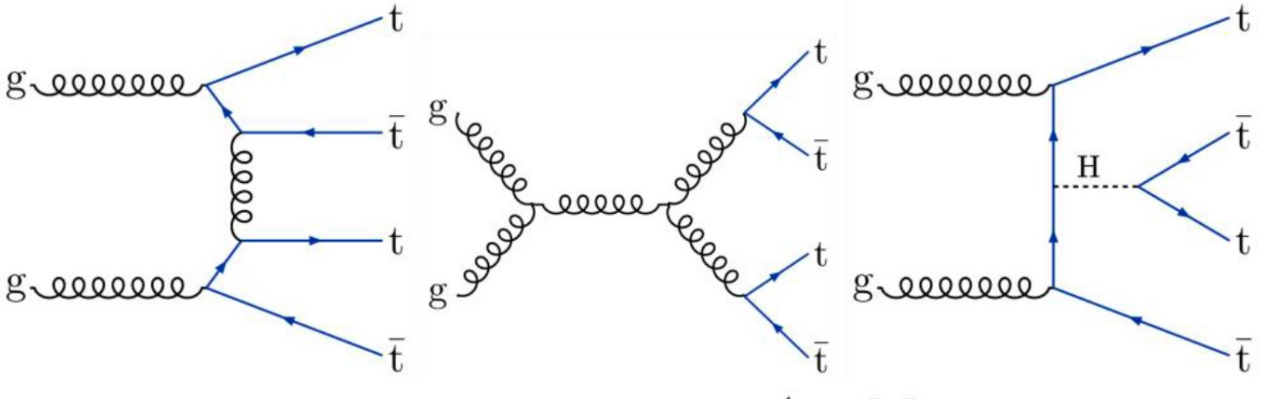
From the YR (2018):
“The production of four top quarks is one of the rare processes in top quark physics that has large sensitivity to variety of new physics effects (including effective field theory sensitivity and sensitivity to anomalous top-Higgs couplings), while at the same time it is interesting in the Standard Model context as a complex QCD process.

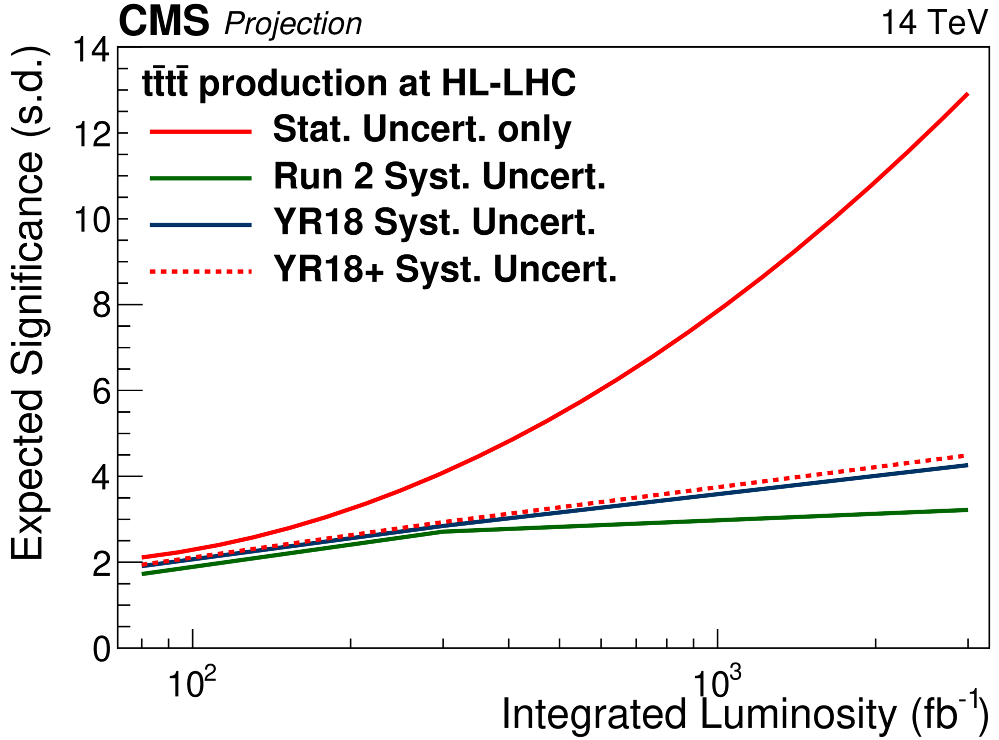
The production of tttt is a rare SM process that is expected to be discovered by future LHC runs, including HL-LHC…

5 years later: CMS (ATLAS) announces evidence (observation) of the process!!!
fully differential measurement at HL-LHC?

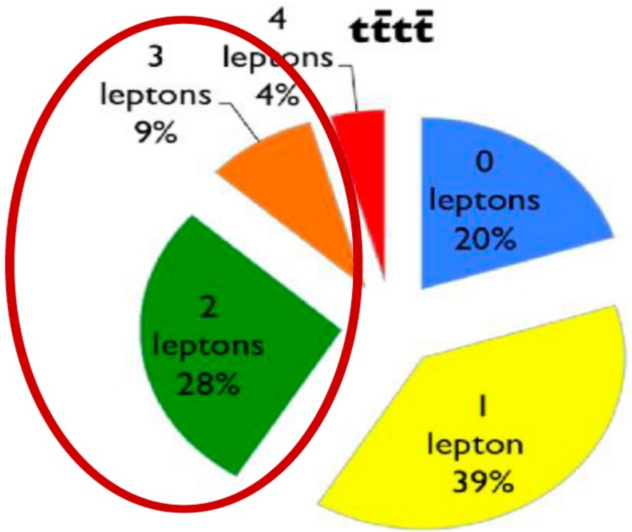
4 tops production

- Rare process sensitive to BSM Physics
- **Current sensitivity 1σ with events with two or three leptons (during YR studies)**
- Expected uncertainty @HL-LHC 20-30%
- Expect evidence of tttt with $3ab^{-1}$ at HL-LHC





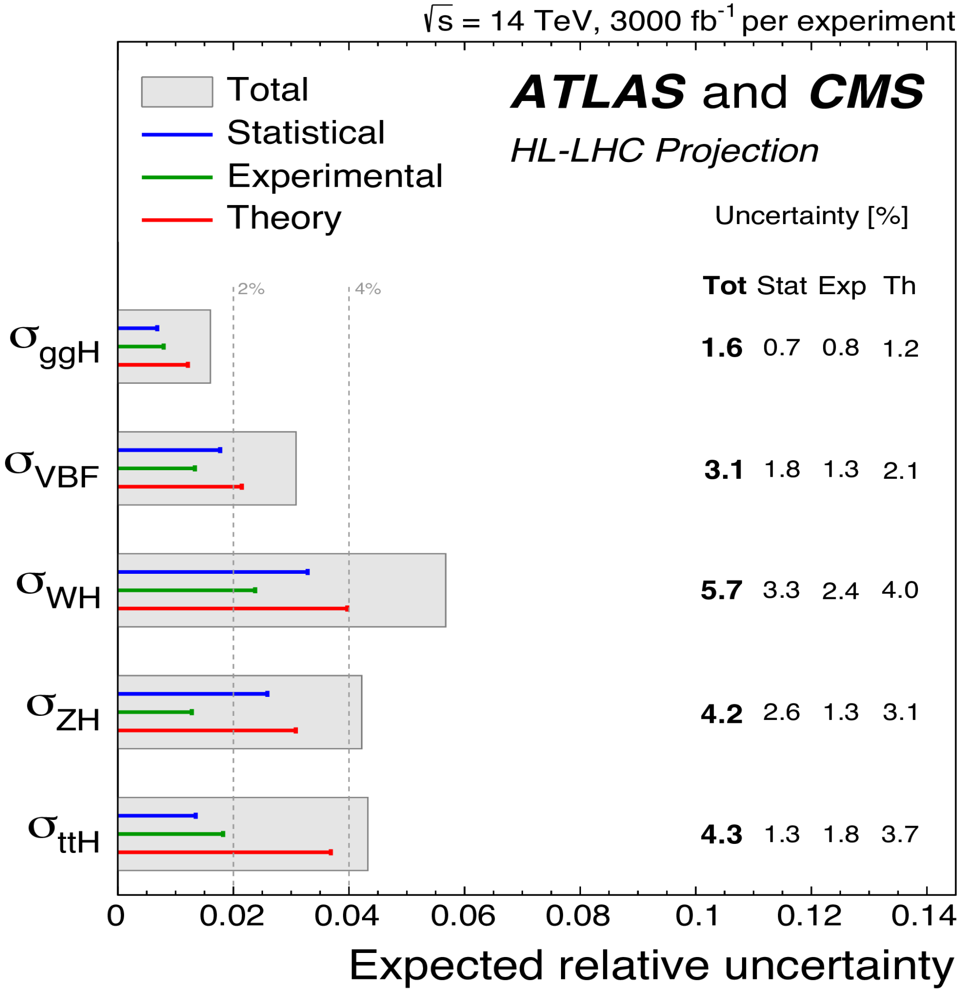
Int. Luminosity	$\sqrt{s}$	*Stat. only* (%)	*Run-2* (%)	*YR18* (%)	*YR18+* (%)
300 fb^{-1}	14 TeV	+30, −28	+43, −39	+36, −34	+36, −33
3 ab^{-1}	14 TeV	±9	+28, −24	+20, −19	±18
3 ab^{-1}	27 TeV	±2	+15, −12	+9, −8	+8, −7
15 ab^{-1}	27 TeV	±1			



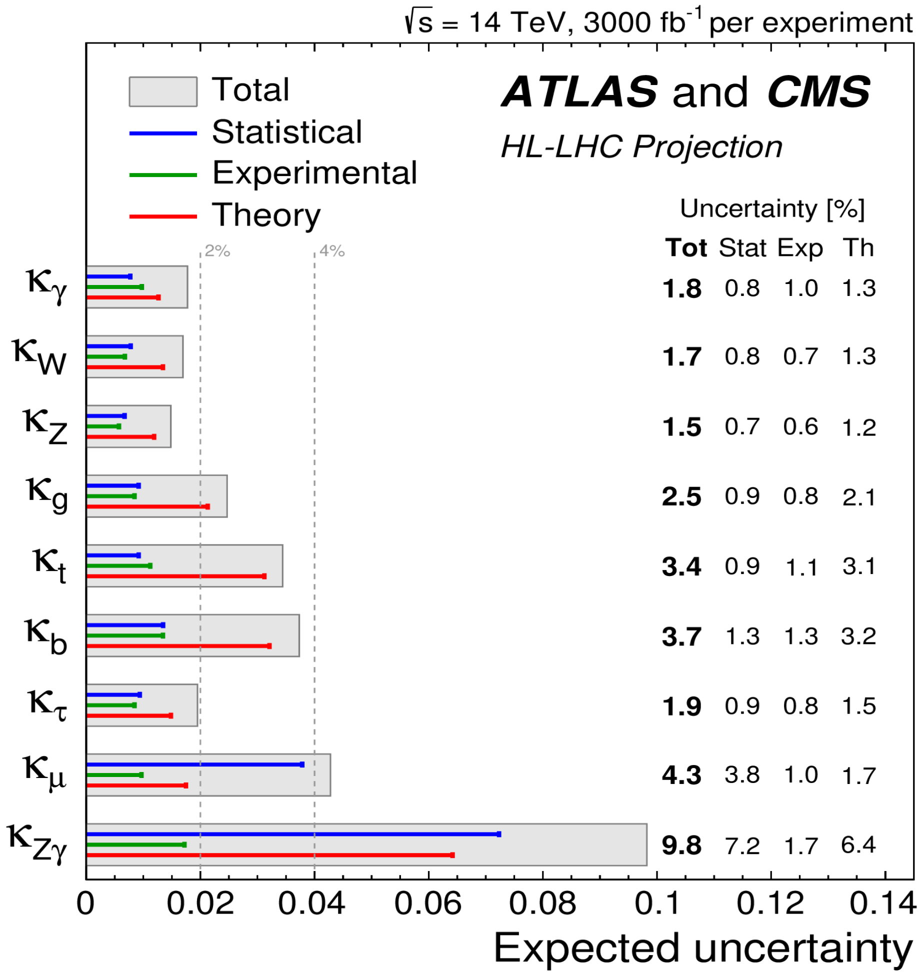
Higgs boson measurements at HL-LHC

Cross sections and Couplings

Production cross sections



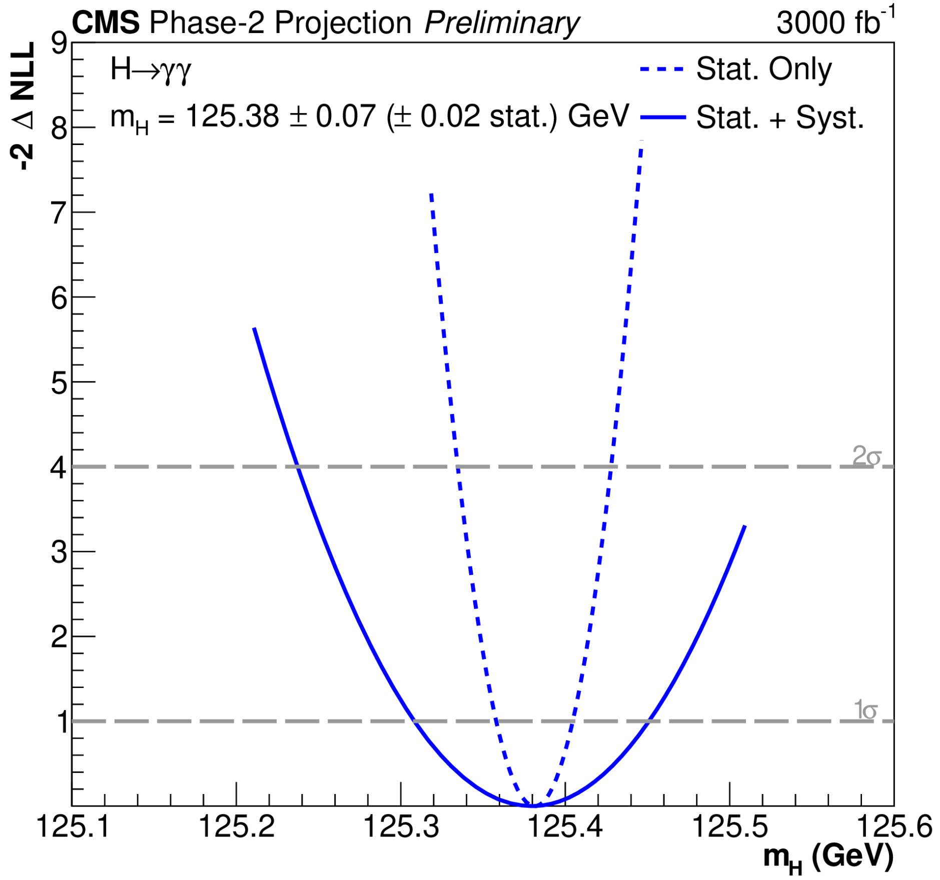
Couplings



- Expected precision reaching 2 - 5% at the end of HL-LHC (CMS+ATLAS)
- Large impact of theory uncertainty in many cases (despite the /2)

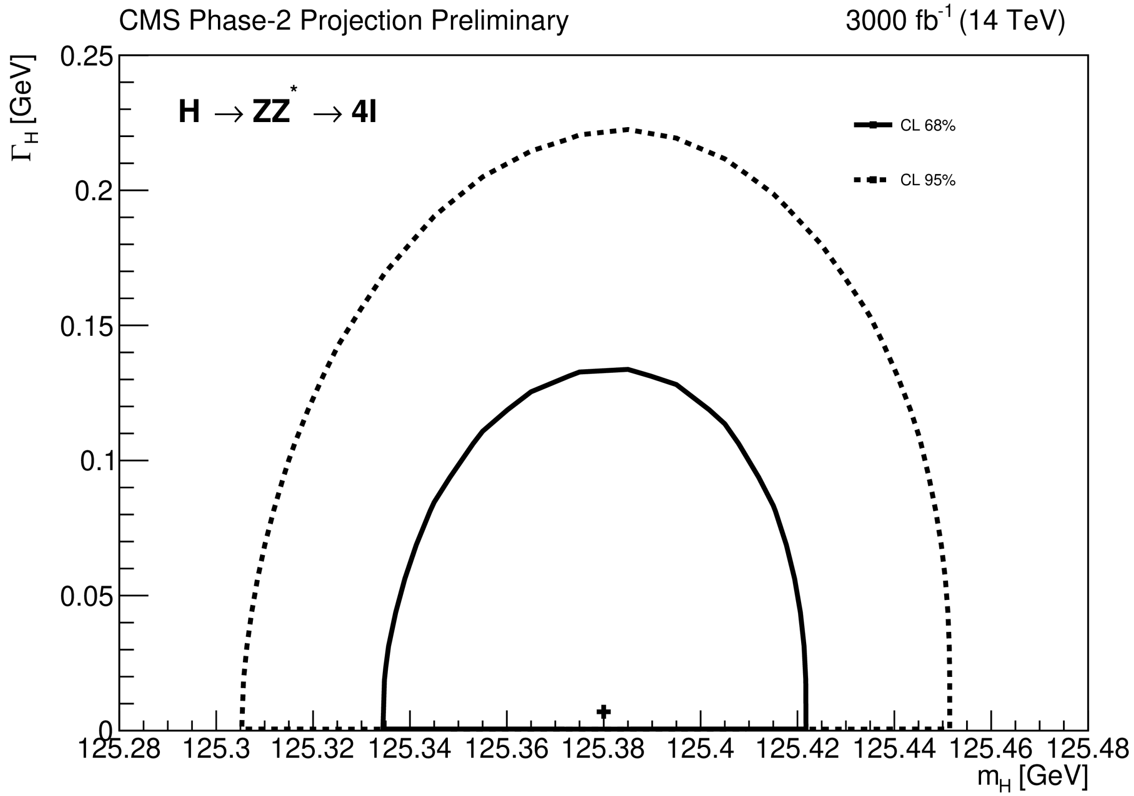
Higgs Boson Mass and Width

Mass in H→γγ



Total uncertainty on m_H: **70 MeV**
Limited by photon energy scale (~0.05%)

Mass vs width in H→ZZ→4ℓ



Total uncertainty on m_H: **25–30 MeV**
comparable stat. and syst. unc.
Direct constraint on width: **Γ_H < 177 MeV**

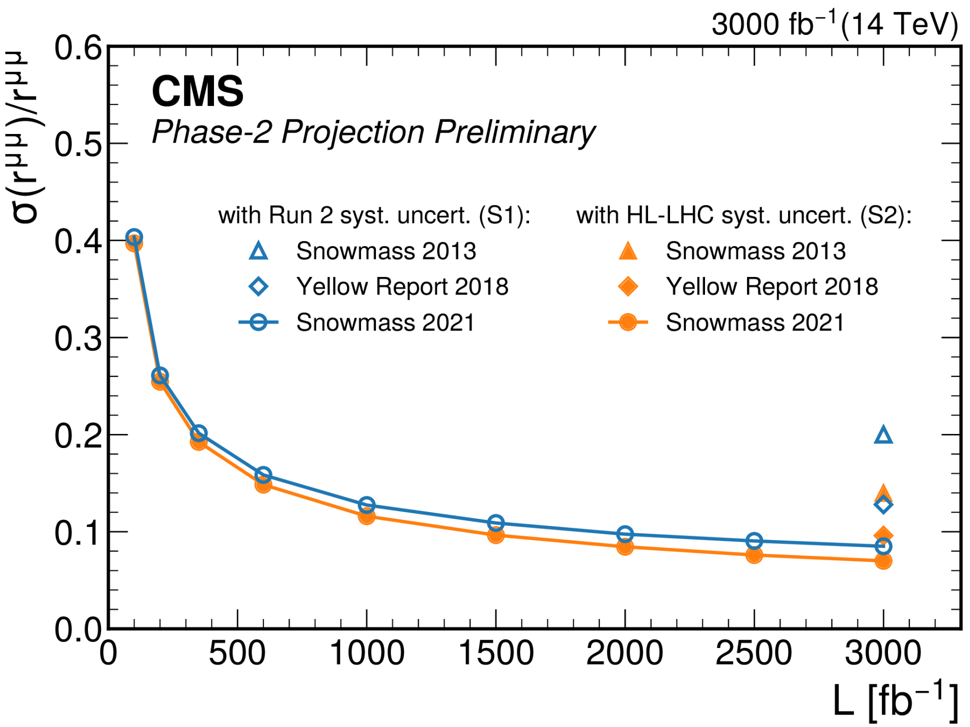
Prospects for H→ μμ

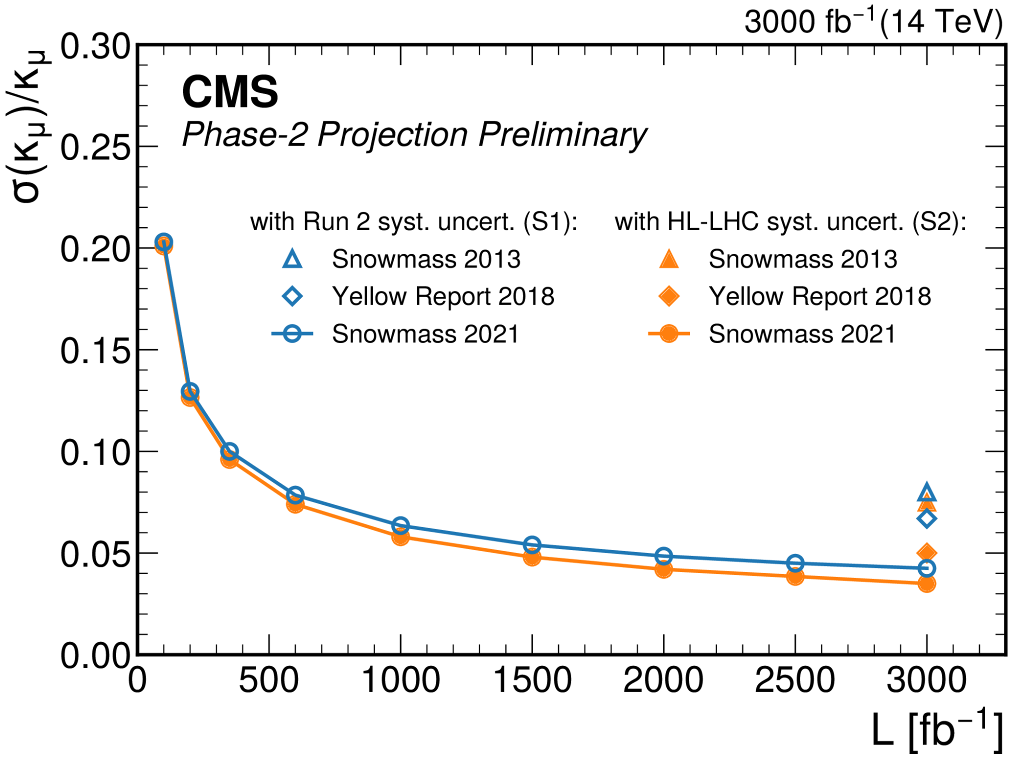
New projection based on the CMS full Run 2 analysis

3—4% uncertainty on κ_μ at HL-LHC

~30% improvement compared to YR18

largely due to improved analysis strategy



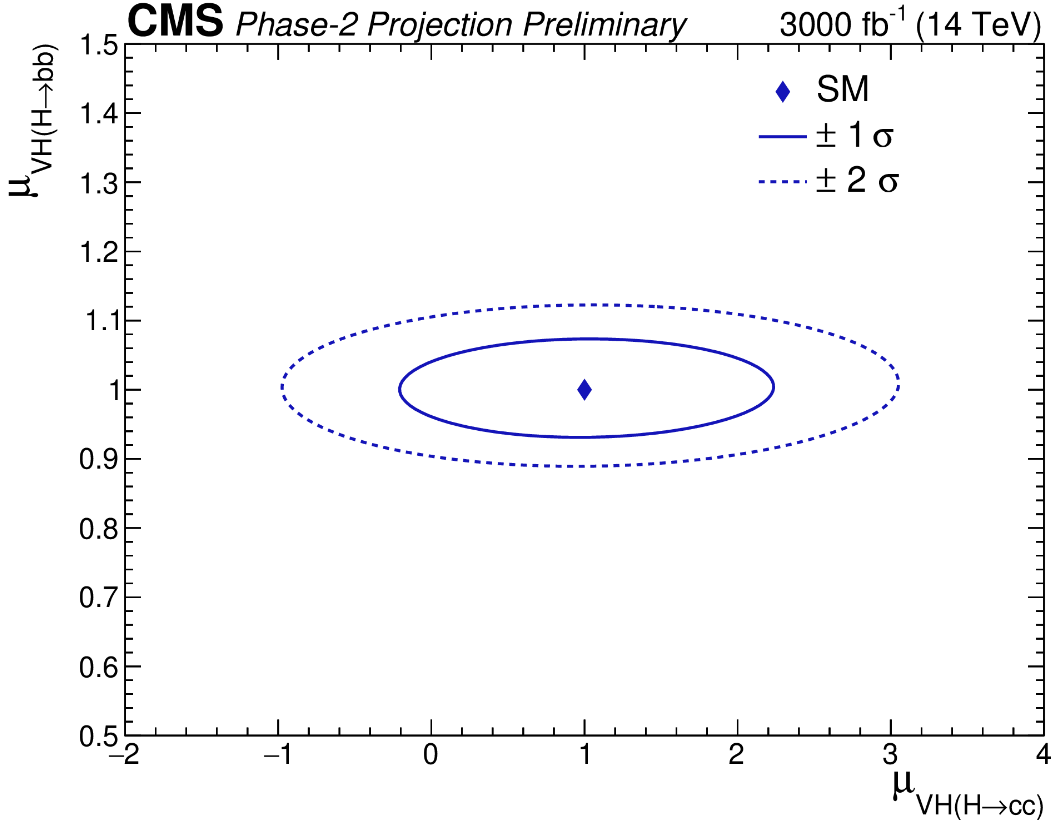


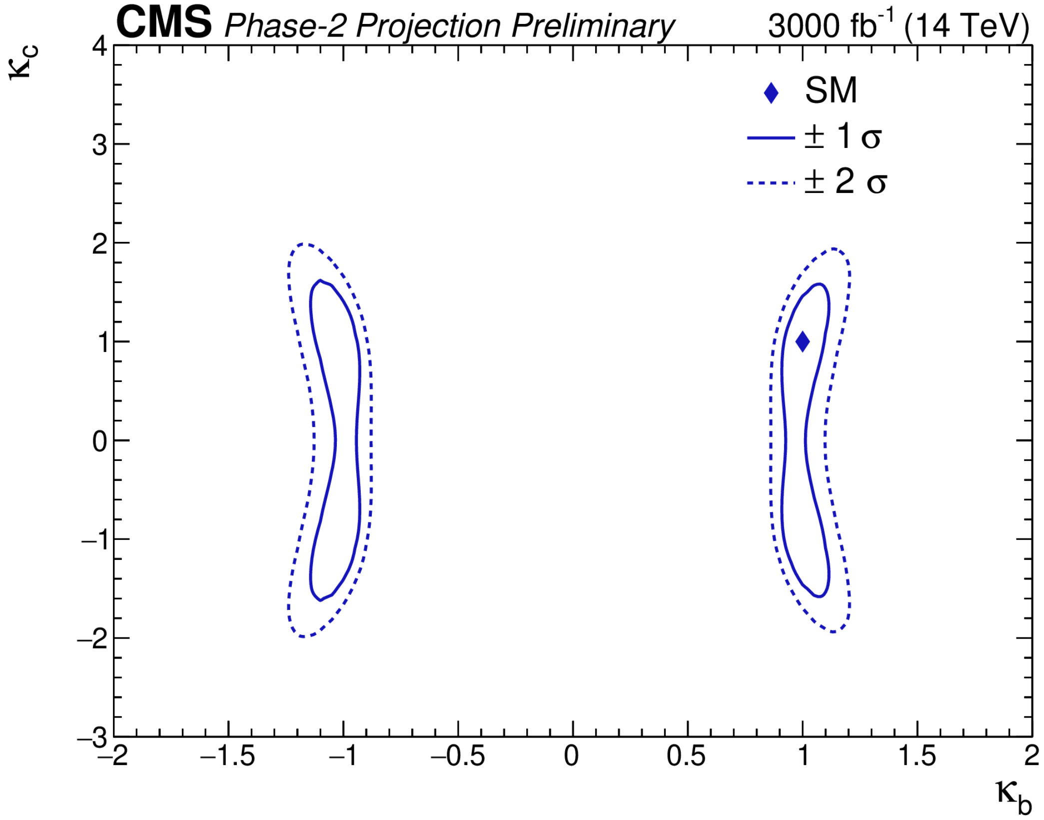
Prospects of VH(H → cc) search

Projection of the Run 2 analysis to HL-LHC

Merged-jet topology with large-R jet p_T

Simultaneous constraint of H → bb and H → cc





Expected sensitivity approaches the SM value for the Higgs-charm coupling

ttH, H → bb with opposite-sign dileptons

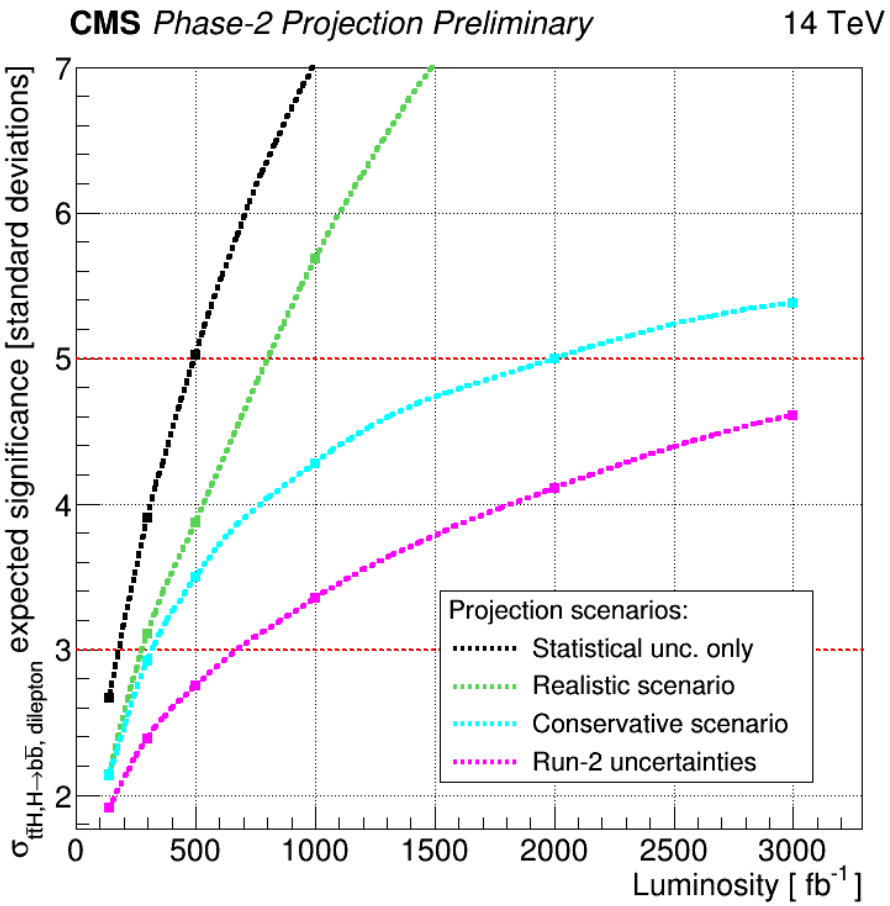
Projection of ttH, H → bb with new method based on CMS-PAS-HIG-18-030

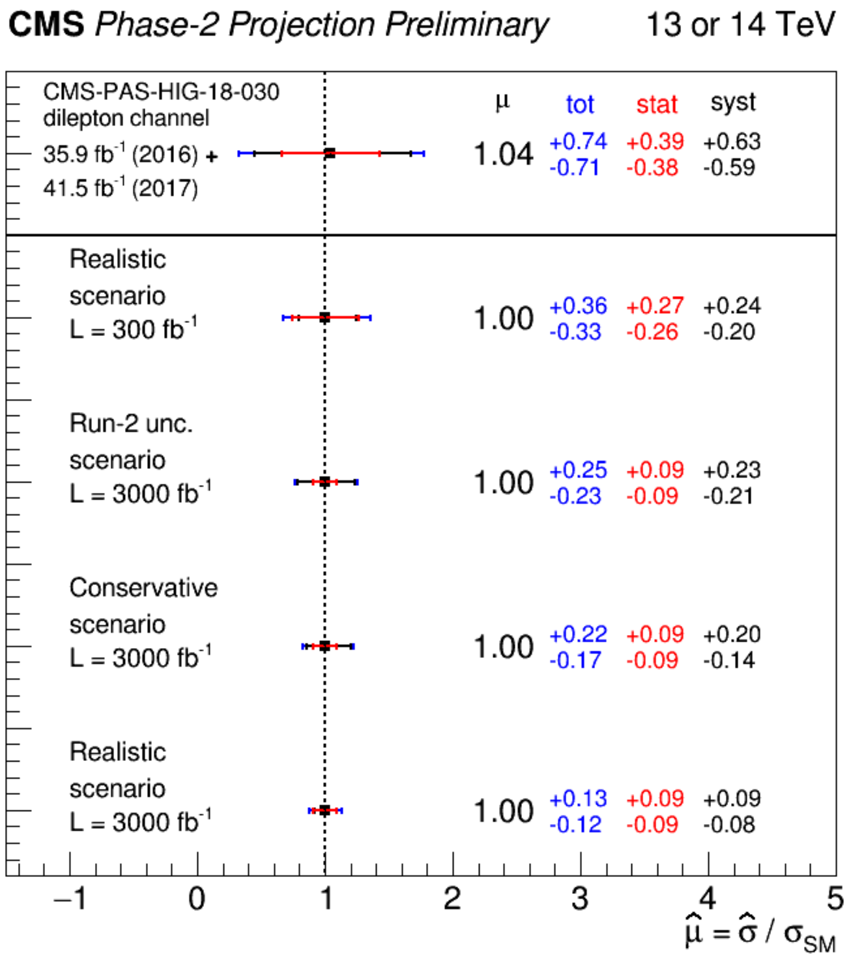
Use a neural network to suppress tt+bb background

5σ discovery:
possible with ~800 fb-1

Run 2 combined sensitivity:
3.9 (3.5) σ obs (exp)

Expected significance vs. integrated luminosity; signal strength modifier for different systematics scenarios.

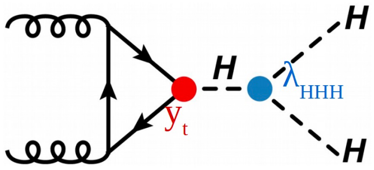


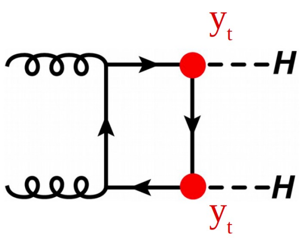


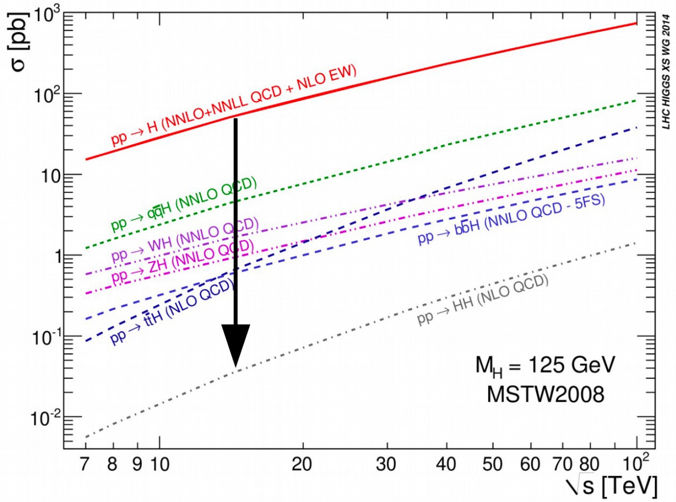
Higgs boson pair (HH) prospects at HL-LHC

Higgs boson pair production and decay

- **Non-resonant production:** **rare** process in the SM
  - Production is dominated by gluon fusion
    - Other rarer modes (ex: VBF HH production)
  - **$\sigma(gg\to HH) \approx 0.1\% * \sigma(gg\to H)$**
  - **Small σ_{HH}** $\Rightarrow$ need high luminosities
  - **Direct determination of λ from Higgs boson pair production**

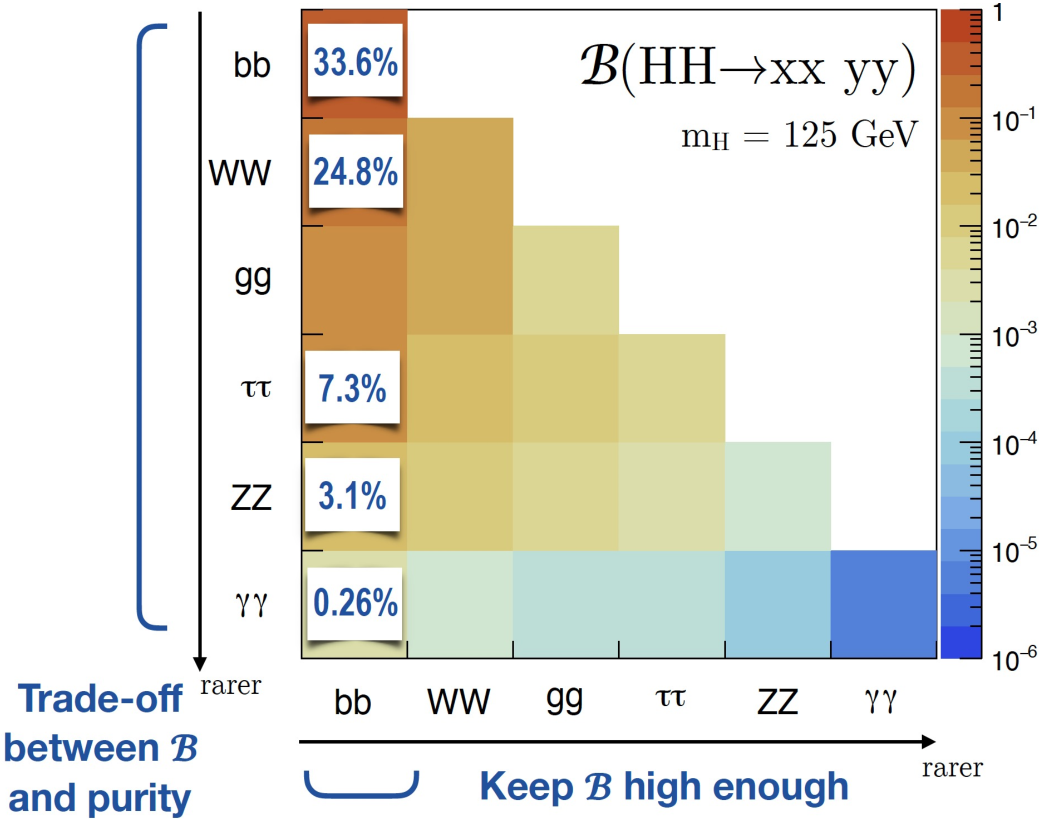






- BSM contributions can modify the Higgs boson coupling parameters and modify the HH cross section: define $\kappa_\lambda = c_{hhh} = \lambda_{HHH} / \lambda_{HHH}^{SM}$

Decay



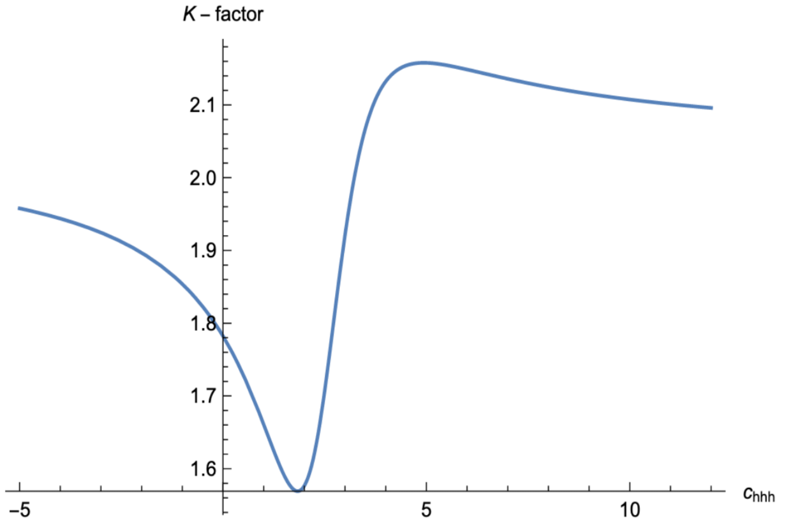
- Phenomenologically rich set of decay channels
  - Broad experimental coverage to increase sensitivity
- Many different signatures
  - All benefit from the upgraded CMS detector

Higgs boson pair production cross section (1)

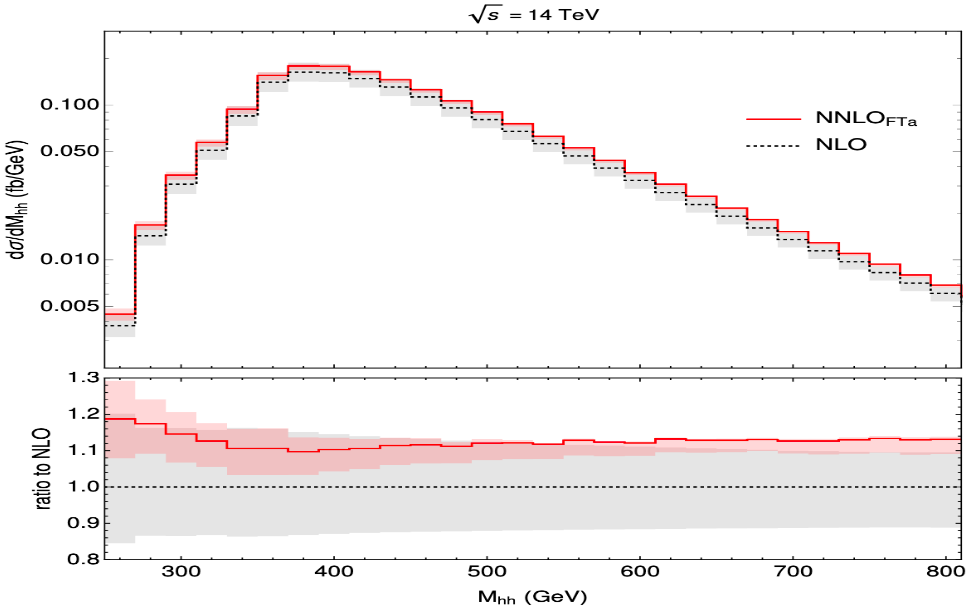
- SM calculation
  - ggF: State of the art NNLO with finite m_t effects
  - Other production modes: NLO with full m_t dependence
- Higgs **self-coupling variations** with full m_t dependence at NLO
  - LO to NLO K-factors vary from 1.57 to 2.16

$\sqrt{s}$ [TeV]	$\mathrm{NNLO_{FTa}}$ [fb]	m_t unc.	PDF unc.	α_S unc.	PDF+α_S unc.
14	$36.69^{+2.1\%}_{-4.9\%}$	$\pm2.7\%$	$\pm2.1\%$	$\pm2.1\%$	$\pm3.0\%$
27	$139.9^{+1.3\%}_{-3.9\%}$	$\pm3.4\%$	$\pm1.7\%$	$\pm1.8\%$	$\pm2.5\%$

$\sqrt{s}$ (TeV)	ZHH	WHH	VBF HH	$ttHH$	$tjHH$
14	$0.359^{+1.9\%}_{-1.3\%} \pm 1.7\%$	$0.573^{+2.0\%}_{-1.4\%} \pm 1.9\%$	$1.95^{+1.1\%}_{-1.5\%} \pm 2.0\%$	$0.948^{+3.9\%}_{-13.5\%} \pm 3.2\%$	$0.0383^{+5.2\%}_{-3.3\%} \pm 4.7\%$
27	$0.963^{+2.1\%}_{-2.3\%} \pm 1.5\%$	$1.48^{+2.3\%}_{-2.5\%} \pm 1.7\%$	$8.21^{+1.1\%}_{-0.7\%} \pm 1.8\%$	$5.27^{+2.0\%}_{-3.7\%} \pm 2.5\%$	$0.254^{+3.8\%}_{-2.8\%} \pm 3.6\%$

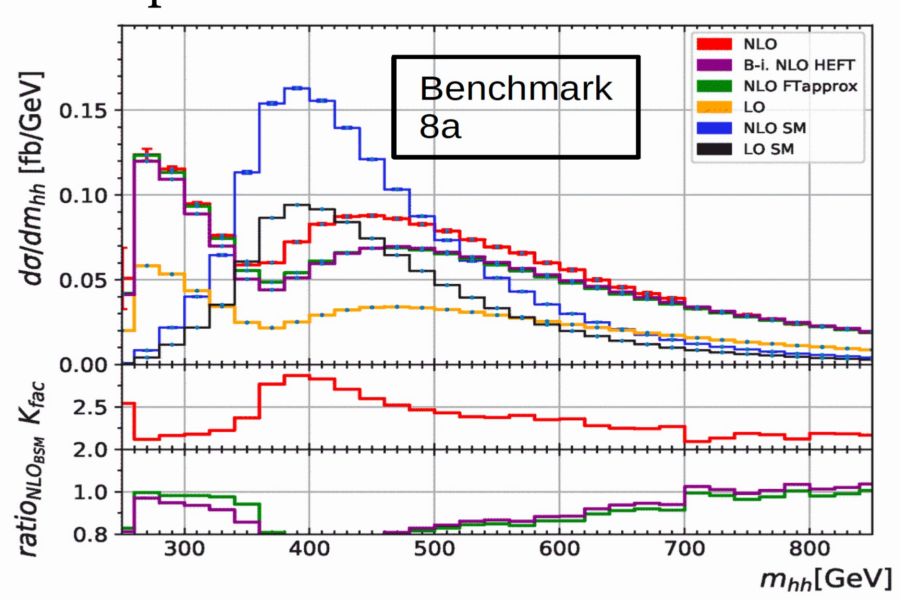


m_{HH} differential cross sections

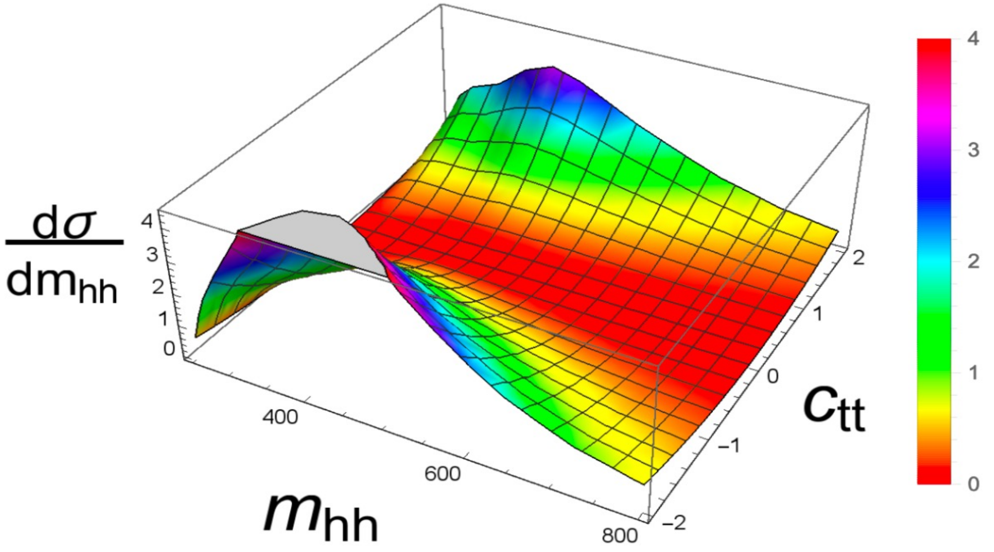


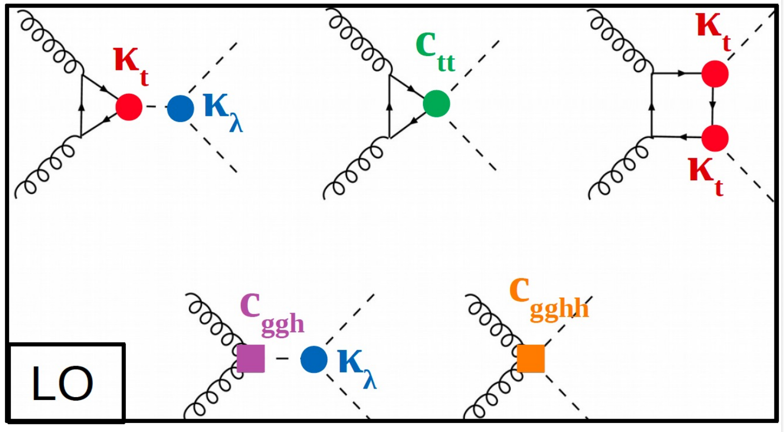
Higgs boson pair production cross section (2)

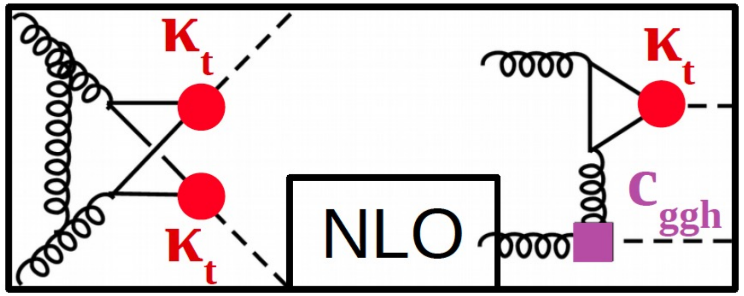
- **BSM model:** Non-linear EFT
- Cross sections and m_{hh} at NLO QCD for some selected benchmark points



- Full NLO results are obtained for any values of the 5 modifying parameters



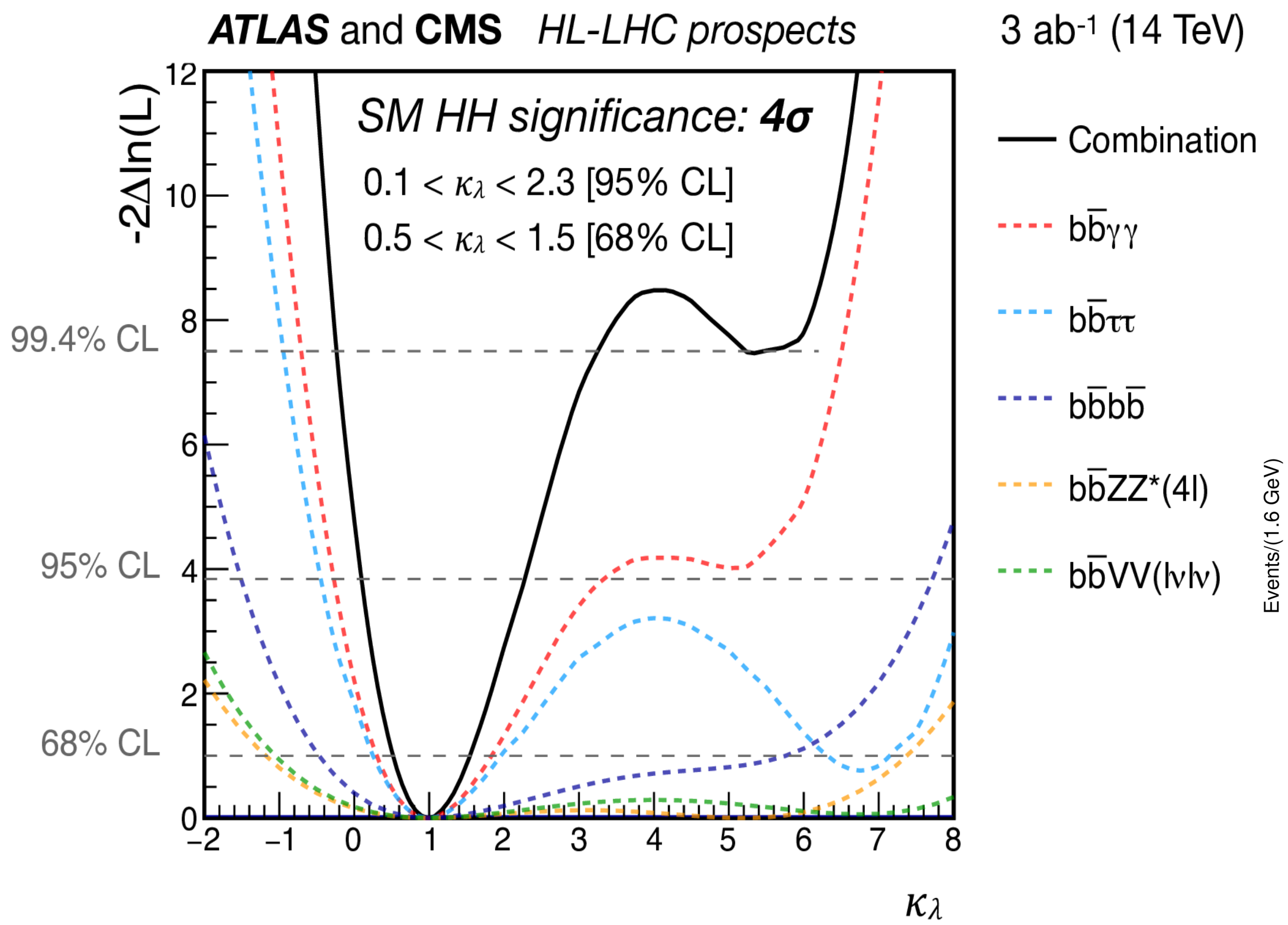




Benchmark	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
5a	1	1	0	2/15	4/15
6	2.4	1	0	2/15	1/15
7	5	1	0	2/15	1/15
8a	1	1	1/2	4/15	0
SM	1	1	0	0	0

HH Experimental prospects

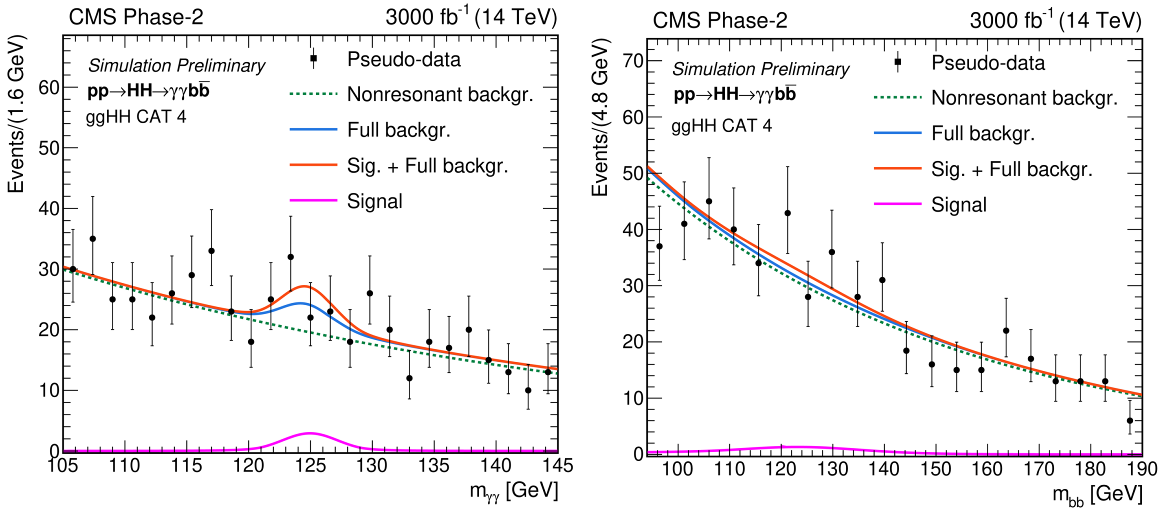
- Expected **significance** with and without systematics at HL-LHC
  - **4σ expected with ATLAS+CMS!**



	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined		Combined	
	4.5		4.0	

DNNs for signal/background discrimination in event selection.

HH → bbγγ : 2.16 σ (for ggHH+VBFHH)



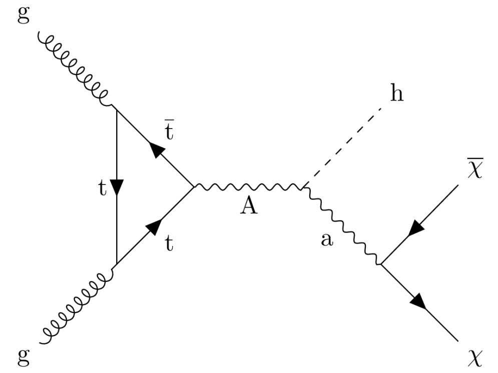
Dark Matter

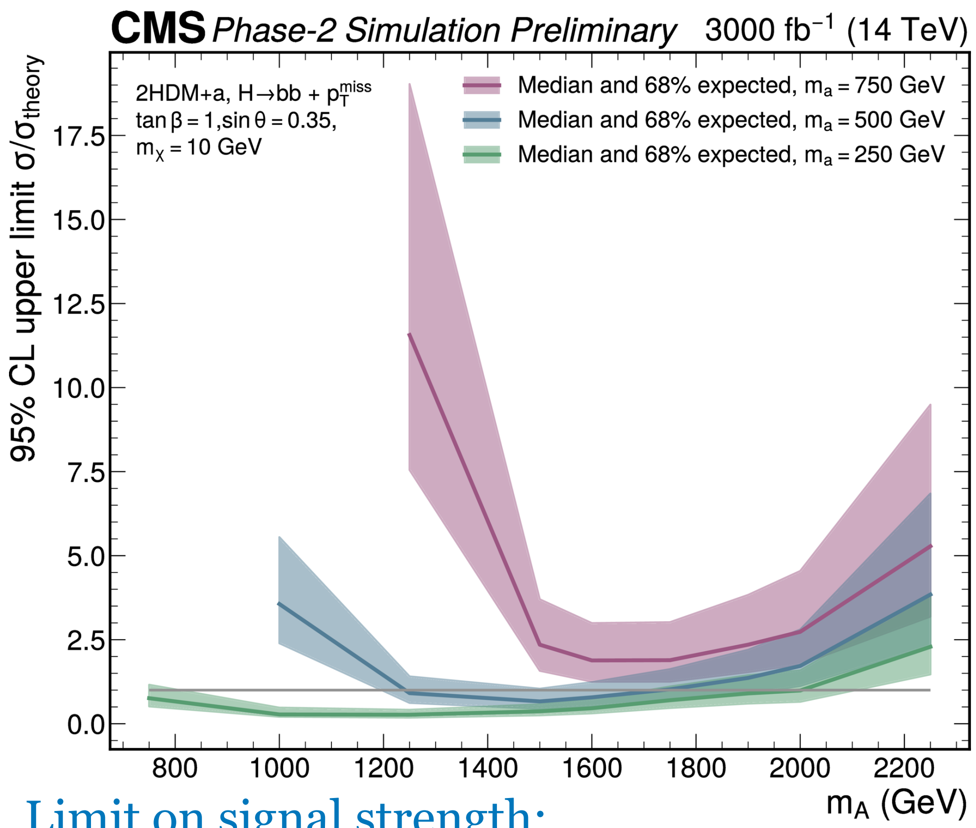
H → bb + MET

Search for boosted mono Higgs, with h → bb + dark matter using Delphes:

- ML-based boosted Higgs tagging on AK8 jets; ETmiss > 200 GeV.
- Interpretation in terms of a Type-II 2HDM+a model:

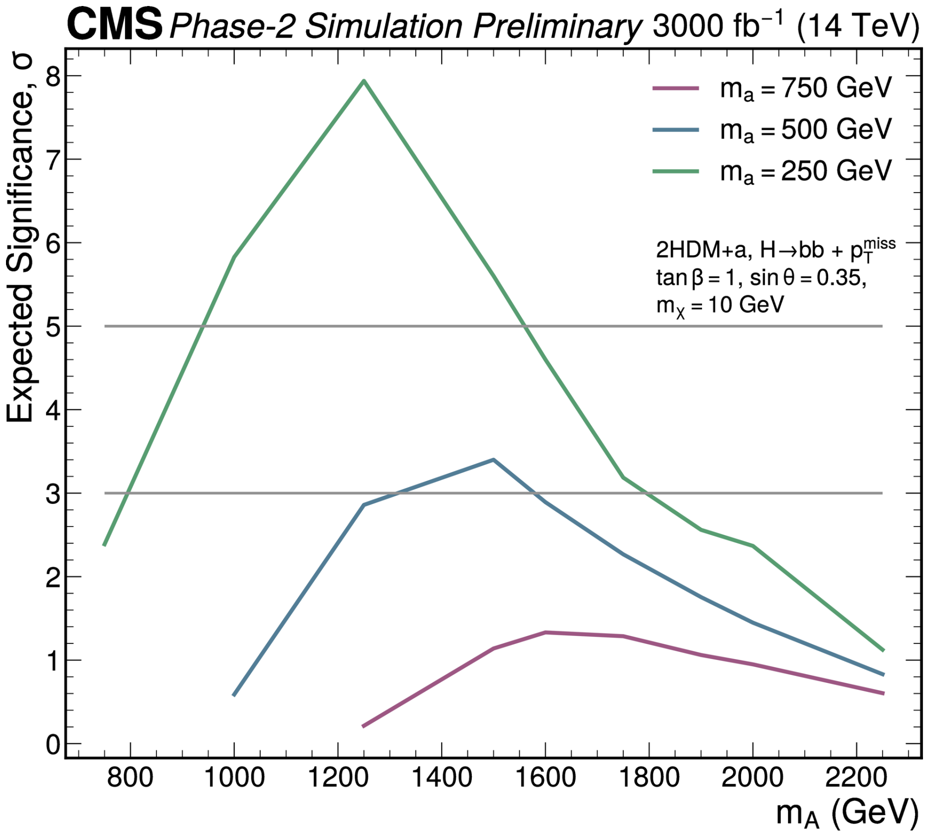
tanβ = 1, sinθ = 0.35, mχ = 10 GeV





Limit on signal strength:

Exclude masses 1 < mA < 2 TeV for ma < 500 GeV



Significance: 5σ discovery for mA ~1-1.6 TeV, ma = 250 GeV

Summary

- Studies for the Yellow Report and White Paper covered a substantial part of the HL-LHC physics phase space.
- Exploring new ideas are encouraged, in particular final states only accessible at HL-LHC and studies exploiting Phase-2 detector features.
  - di-Higgs and long-lived particles are obvious examples.

Thanks